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Methods of Evaluating Protective Clothing Relative to Heat and Cold Stress: Thermal Manikin, Biomedical Modeling, and Human Testing

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Personal protective equipment (PPE) refers to clothing and equipment designed to protect individuals from chemical, biological, radiological, nuclear, and explosive hazards. The materials used to provide this protection may exacerbate thermal strain by limiting heat and water vapor transfer. Any new PPE must therefore be evaluated to ensure that it poses no greater thermal strain than the current standard for the same level of hazard protection. This review describes how such evaluations are typically conducted. Comprehensive evaluation of PPE begins with a biophysical assessment of materials using a guarded hot plate to determine the thermal characteristics (thermal resistance and water vapor permeability). These characteristics are then evaluated on a thermal manikin wearing the PPE, since thermal properties may change once the materials have been constructed into a garment. These data may be used in biomedical models to predict thermal strain under a variety of environmental and work conditions. When the biophysical data indicate that the evaporative resistance (ratio of permeability to insulation) is significantly better than the current standard, the PPE is evaluated through human testing in controlled laboratory conditions appropriate for the conditions under which the PPE would be used if fielded. Data from each phase of PPE evaluation are used in predictive models to determine user guidelines, such as maximal work time, work/rest cycles, and fluid intake requirements. By considering thermal stress early in the development process, health hazards related to temperature extremes can be mitigated while maintaining or improving the effectiveness of the PPE for protection from external hazards.

Keywords health hazard assessment, thermal strain, thermoregulation

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INTRODUCTION

One of the most serious health hazards related to personal protective equipment (PPE) is thermal stress. PPE is designed to protect against natural or human-made hazards, such as chemical, biological, radiological, nuclear, and explosive hazards, and includes fire fighting, first responder, HAZMAT, and certain occupational and combat uniforms.[1] PPE ranges from garments designed to protect from spills, to fully encapsulated protective suits with rebreathing apparatus, to the inclusion of body armor and helmets.

The combination of PPE characteristics, environmental conditions, and required physical activity can result in thermal stress. Heat stress is elevated by multiple factors when wearing PPE. Added weight, bulk, and a layering effect of the addition of PPE all increase metabolic demands.[2] PPE also increases insulation and reduces water vapor permeability, both of which

Nomenclature

The following terms are used in the biophysical evaluation of the thermal characteristics of fabrics and clothing.

clo = Unit of thermal resistance to heat flow through textile material (*Insulation*). 1 clo = 6.46 W/m^2 of surface area per degree Celsius difference between skin and ambient temperatures. A nude person has insulation of 0 clo; a typical business suit is equivalent to 1 clo. Insulation is reduced by increased moisture content and air movement within clothing.

i_m = Water vapor permeability index for evaporative heat loss (*Permeability*). Permeability is the ratio of the evaporative resistance of the fabric relative to that of air. Values range from 0 (impermeable) to 1 (most desirable). PPE designed to protect against biological and chemical hazards often is impermeable, resulting in little potential for evaporative heat loss.

i_m/clo = Ratio of permeability to insulation (*Evaporative Resistance*). The higher the i_m/clo ratio, the greater the potential for evaporative heat loss and therefore cooling.

limit the ability to dissipate heat and evaporate water vapor from sweat.[3] This can increase body core temperature and limit work intensity or duration. During cold exposure, heat stress can occur if PPE is worn in combination with extreme cold weather clothing while working at a high metabolic rate; however, during rest periods, excessive heat loss can occur, particularly if clothing has become wet from sweat or precipitation.[4,5] In the cold, extremity (hand, foot) temperatures, rather than body core temperature, may be the critical factor for health and performance.[5]

All new clothing and equipment for the military undergoes a health hazard assessment that evaluates health and performance risks associated with various hazards, including temperature extremes of heat and cold.[6] The physiologists, biophysicists, and physicians at the U.S. Army Research Institute of Environmental Medicine (USARIEM), in concert with the industrial hygienists at the U.S. Army Public Health Command, use a multidisciplinary approach in evaluating PPE to ensure the health and safety of individuals working in thermally stressful environments. This systematic evaluation includes biophysical evaluations to determine insulation and permeability of textiles on a guarded hot plate and ensembles on a thermal manikin; biomedical modeling to predict thermal strain, including work limits and fluid requirements; and human testing to quantify physiological responses in a controlled laboratory setting that simulates the conditions under which the PPE will be used if fielded. This three-tiered approach provides much more information than any single test method and is a critical part of health hazard assessments.

Typically, development of new PPE focuses on improving the level of protection from external hazards. This must be done without compromising thermal strain that can limit work unless it is determined that the benefit of increased protection outweighs the impact of added thermal stress. This review outlines the process used by the U.S. Army to evaluate new PPE for protecting health and performance with respect to temperature extremes. If this is considered early in the development process, health hazards related to temperature extremes can be mitigated while maintaining or improving the effectiveness of the PPE for protection from external hazards.

While some examples of PPE presented in this review are specifically for military use, other applications include Homeland Security, law enforcement, and fire fighting. Military PPE is sometimes adapted for industry use, and commercial PPE may be adapted for military use if it meets the criteria. Thus, a wide range of clothing developers could benefit from understanding the process of evaluation of thermal stress where the goal is to allow workers to be more productive for longer periods when working in temperature extremes.

Terminology

Thermal "stress" refers to the environmental conditions that cause an individual to gain or lose heat; whereas thermal "strain" refers to the physiological responses of the individual to the stressors. Environmental conditions (temperature, humidity, radiant load, wind speed); physiological factors (e.g., anthropometrics, fitness, hydration, nutrition, acclimatization, rest/fatigue, health, medication); and work-related factors (e.g., uniform, load carriage, terrain, work rate) all interact to produce thermal strain.[7,8] Physiological signs of heat strain include increased sweat rate, increased heart rate, and elevated body (core and skin) temperatures. Physiological signs of cold strain include decreased skin temperature (particularly extremity temperatures), elevated metabolic rate (shivering), and decreased body core temperature.

BIOPHYSICAL EVALUATIONS

The initial testing of clothing systems begins with a biophysical evaluation of textile materials, followed by evaluation of the actual PPE on a thermal manikin.[9,10] Currently-fielded textile materials and clothing systems are typically used as controls for comparative evaluations. Thermal characteristics (thermal insulation (clo) and water vapor permeability (i_m)) of textile samples are measured using a guarded hot plate,[11] while the thermal characteristics of ensembles are determined using a thermal manikin. These data are used to calculate evaporative resistance (i_m/clo), which is used to compare the evaporative cooling or heat loss capacity of each ensemble.

Guarded Hot Plate

Guarded hot plate (GHP) testing measures the dry and wet (evaporative) heat transfer through single- or multiple-layered textile materials to determine insulation and permeability values.[11,12] A small (~35 cm^2) sample of material is placed on a temperature-controlled flat plate in a controlled environmental chamber, with measurements made according to the ISO 11092.[12] The procedure is designed to simulate the heat transfer that occurs in the microclimate created between the human skin surface and the textile material (i.e., clothing), and through the material itself to the surrounding ambient atmosphere. An advantage of GHP testing is that it can quickly evaluate and rank a large number of similar materials. However, the thermal resistance and vapor permeability values measured for a flat, two-dimensional sample may not be the same when the material is used to construct an actual garment, where adding seams and fasteners may change the properties. Therefore, a material typically only proceeds for evaluation in garment form on the thermal manikin if GHP tests show that it is significantly better than the standard or control material (>0.1 clo or >0.03 i_m/clo difference), and/or if the material passes a selection based on ranking. Alternatively, if new PPE has properties that provide significantly improved protection from hazards, manikin testing may be conducted to determine the trade-off in terms of increased thermal stress.

Thermal Manikin

Thermal manikin (TM) testing measures dry and wet heat transfer of PPE worn by a heated, sweating manikin in a controlled environmental chamber. The advantage of TM testing over guarded hot plate alone is that heat transfer characteristics are evaluated on a complete ensemble as it is designed to be worn, accounting not only for the properties of the specific textiles but also for garment design and drape on the manikin form, as well as the added influence of personal equipment, such as body armor or wearable rebreathing apparatus. Articulated manikins simulating human locomotion also measure the effect of air movement within the microclimate, i.e., the air space between the skin and the garment, on heat and water vapor transfer. While loose garments that allow a larger air gap in the microclimate provide greater insulation in static conditions, physical movement pumps air through this space and possibly through the garment itself, effectively reducing insulation.[13]

Thermal insulation and evaporative cooling potential (permeability) of clothing ensembles are evaluated using accepted standard operating procedures on a life-sized TM.[10,14–19] The TM is equipped with computer-controlled capabilities to automatically adjust the power supplied to the heating elements to maintain a constant skin temperature regardless of the PPE worn. The TM is outfitted with a tight, formfitting suit that can simulate a sweating human with a 100% wetted surface area by saturating the suit with water. The sweating TM pumps heated water through pores to the skin surface of the manikin, and sweating rate is computer controlled.

The standard operating procedures used in TM evaluations include regulation of the manikin surface at a constant temperature and controlling ambient temperature, relative humidity, and air velocity in the climatic chamber housing the manikin. The most widely accepted test procedures for the operation of a TM are published by ASTM International. ASTM F 1291-10, "Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin,"[15] describes measurement of the insulation value of a complete clothing ensemble. It requires a TM surface temperature of 35°C and a climatic chamber controlled at 23°C, 50% relative humidity with a 0.4 m/sec air velocity. ASTM F 2370-10, "Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin"[14] measures the permeability of a complete clothing ensemble. It requires a TM surface temperature of 35°C, 100% saturated skin surface, and a climatic chamber controlled at 35°C, 40% relative humidity, with a 0.4 m/sec air velocity. In addition to the tests conducted at 0.4 m/sec, USARIEM also conducts tests at two higher wind speeds to allow accurate determination of the effect of increased air movement on the thermal transfer properties of the clothing.[20] This effect can be seen in Figure 1 for several clothing ensembles. A higher wind speed has a greater effect on garments with a higher evaporative resistance ratio, whereas wind has little effect on PPE of low permeability and therefore a low evaporative resistance ratio.

If TM tests indicate there is a large enough difference in evaporative resistance between prototype PPE and the current PPE (e.g., i_m/clo >0.1), it is usually recommended that the prototype ensemble be evaluated during a controlled human wear test, since this would also likely produce differences in markers of physiological strain, such as core temperature or heart rate. When TM differences are small, prediction modeling alone may be used for further evaluation, although human testing may still be requested to document physiological responses.

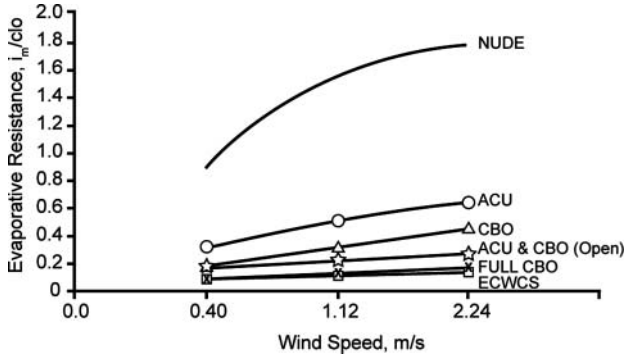

FIGURE 1. The effect of wind speed on Evaporative Resistance is shown for a nude manikin, and when wearing the Army Combat Uniform (ACU), Chemical Biological Overgarment (CBO), and Extended Cold Weather Clothing System (ECWCS). ACU & CBO (Open): CBO jacket is left open for ventilation; mask and gloves are carried. Full CBO: CBO is closed; mask and gloves are worn.

BIOMEDICAL MODELING

Biomedical modeling presents a means of estimating physiological strain (e.g., body temperatures, sweating, shivering, heart rate) over a variety of environmental and metabolic conditions.[21] The thermal characteristics of PPE determined through biophysical evaluations are important to the models for accurate determination of heat and vapor transfer. These models are especially valuable when a large number of scenarios (such as multiple environmental conditions and/or multiple PPE) are desired and the cost of testing with human volunteers would be prohibitive.

Models may be empirical, i.e., mathematical functions fit to actual data obtained from human studies, or rational, i.e., based on accepted physical laws and physiological principles. Both are most useful across the range of conditions for which they were developed. Validation of models is an ongoing process, and improvements are made as data from thermal manikin and human studies become available.

Empirical Models

The USARIEM Heat Strain Decision Aid (HSDA) is an example of an empirically developed operational model based on the results of thousands of experiments. Volunteers for these experiments were primarily male soldiers between the ages of 18–25 who were fit for regular duty. They were well rested between trials and performed military duties such as road marching, tank driving, and marksmanship in various climates while their physiological responses were recorded. Results obtained from the HSDA, therefore, reflect the physiological responses of this particular population, although the tasks performed represent a range of metabolic activity and could be related to tasks required in other occupations, such as sustained aerobic activity, vehicle operation, and assembly line or machine supervision. Inputs to this model, shown in Table I, include environmental conditions, mission-related requirements (e.g., work intensity or work / rest cycles), and anthropometric characteristics known to affect thermoregulatory responses. Clothing parameters derived from thermal manikin evaluations are also used as inputs in this model and provide critical information about heat transfer. Heat acclimatization and hydration status are also important because of the impact they have on thermoregulatory responses.[22] While the output parameters from the HSDA shown in Table II pertain to mission performance, the limits are based on the prediction of core temperature.

Rational Models

In contrast to empirical models that are developed using data from experiments, rational models are constructed using established physiological principles. They are then validated using experimental data that are compared with the predicted outcome from the model. Because they incorporate known physiological responses, they may be more adaptable to account for individual variability in anthropometrics, physical fitness, and responses to heat strain.

TABLE I. Input Variables for the HSDA

Input	Range
Dry bulb temperature (T_{db}) [°C]	$10 \leq T_{db} \leq 50$
Relative humidity (RH) [%]	$0 \leq RH \leq 100$
Wind speed (WS) [m/s]	$0 \leq WS \leq 10$
Mean radiant temperature (T_{mr})[°C]	$T_{db} \leq T_{mr} \leq (T_{db} + 40)$
Altitude (ALT) [m above sea level]	$0 \leq ALT \leq 4000$
Work rate (WR) [W]	$100 \leq WR \leq 800$ (resting- very heavy work)
Acclimatization (Accl) [# of days]	$0 \leq Accl \leq 12$
Dehydration (Dehyd) [%]	$0 \leq Dehyd \leq 6$
Uniform	limited to i_m and clo data from thermal manikin tests
Height (Ht) [cm]	$120 \leq Ht \leq 215$
Weight (Wt) [kg]	$40 \leq Wt \leq 145$

The Six Cylinder Thermal Model (SCTM) and SCENARIO are examples of rational models developed at USARIEM. In the SCTM, the six cylinders represented are torso, each limb, and head.[23] This allows the model to account for redistribution of blood flow to or from the extremities. SCENARIO[24,25] uses a six-compartment model to simulate sweating and circulatory changes under different environmental conditions and metabolic activity levels to predict body core temperature. These compartments include core, muscle, fat, vascular skin, avascular skin, and clothing. Heat production in the model occurs due to basal metabolic rate, exercise, and, under cold conditions, shivering. Heat transfer throughout the body compartments occurs by conduction across tissues and by convection through blood circulation. Heat losses in the model through evaporation, radiation, conduction, and convection depend on the environmental conditions.

TABLE II. Output Parameters from the HSDA

Output	Range
Maximum work time, up to 5 hr (MxWrk) [min]	$0 \leq MxWrk \leq 300$
Water requirements for one-time continous work bout (Wtr) [qt/h]	$0 \leq Wtr \leq 1.5$
Recommended work/rest cycles, up to 5 hr work/rest (WRC) [min/h]	$0 \leq WRC \leq 60$
Water requirements for work rest cycles (Wtr-WRC) [qt/h]	$0 \leq Wtr\_WRC \leq 1.5$
Estimated heat casualties if guidance is not followed (HeatCas) [%]	$0 \leq HeatCas \leq 100$

Sometimes well-accepted rational models are combined with empirical models to expand their use. An example of this is the Probability of Survival Decision Aid (PSDA)[26] model that was developed for the U.S. Coast Guard to estimate mortality due to heat or cold strain during man-overboard incidents. It predicts survival time for hypothermia and dehydration during prolonged exposure at sea in both air and water, such as a victim in the water or floating in an emergency craft. This model combines the Six Cylinder Thermal Model with an empirical water loss equation developed from physiological data.[26] Clothing inputs include heat transfer characteristics of survival suits designed for protection in case of emergency immersion. While the output of interest for the Coast Guard is survival time, this is based on the model's prediction of core temperature, which may be relevant for other applications.

Although, historically, most models at USARIEM have focused on whole-body responses, recent efforts have been devoted to extremity models, such as predicting manual dexterity performance in the cold,[27] or the effect of extremity cooling on lowering brain temperature.[28] Such models could also be used to predict when dexterity degradation (influencing performance) or peripheral cold injury (e.g., frostbite) would occur, and would be useful for evaluation of handwear or footwear[29] for thermal protection.

HUMAN PHYSIOLOGICAL TESTING

Human testing can be conducted independently or in conjunction with biophysical evaluations and biomedical modeling, although ideally all three evaluations will be performed to build a comprehensive understanding of the PPE's influence on human physiological strain under a variety of conditions. Human testing provides the most accurate data on how PPE impacts the physiological strain of a given scenario of work intensity and duration in specific environmental conditions. Movement during exercise, posture during rest, changing body temperatures, and sweat absorption all may affect the thermal characteristics of the PPE and impact thermal strain differently from data obtained on a sweating articulated manikin under standard conditions. In addition to providing data on thermal strain for specific PPE applications, the data from this testing are important for continued refinement of models. Human testing is also critical for evaluation of specialized PPE, such as microclimate cooling systems for use with chemical protective clothing.[30,31] Finally, user acceptability can be obtained by human testing.

Heat Stress

Humans can maintain normal body (core and skin) temperatures within a wide range of environmental conditions, assuming heat transfer is not impaired. Heat dissipation occurs through dry heat loss (radiation and convection) and evaporative heat loss (sweating). Peripheral vasodilation increases blood flow to the skin, enhancing convective heat transfer from the core and increasing sweating.[32] Corresponding cardiovascular changes include increased heart rate and reduced blood flow to the gastrointestinal tract and inactive tissue.[32] Under compensable heat stress conditions, these responses indicate heat strain in an individual.[33] When the heat load exceeds the body's ability to dissipate heat (uncompensable heat stress), heat strain increases and heat illness/injury can occur. Pathological states of heat strain include heat exhaustion, heat injury, and heat stroke.[7] Cognitive and physical performance decrements can occur at hyperthermic and/or dehydration levels lower than those causing heat injury.[34,35] U.S. Army guidance for prevention and management of hot-weather injuries is published in Technical Bulletin Medical 507, *Heat Stress Control and Heat Casualty Management*.[7]

PPE can exacerbate heat strain by limiting heat transfer in individuals working in hot environments. This is particularly true of PPE with limited permeability that blunt evaporative heat loss.[1]

Cold Stress

Physiological responses to cold stress include vasoconstriction and shivering. Peripheral vasoconstriction reduces convective heat transfer between the body's core and shell (skin, subcutaneous fat, and skeletal muscle), thereby limiting heat loss. Vasoconstriction begins as skin temperature falls below about 35°C and becomes maximal when skin temperature is about 31°C.[36] As cooling continues, the temperature of underlying tissues also falls, resulting in decreased function of nerves, muscles, and joint mobility, all of which degrade physical performance.[37] Extremity (hands, feet) temperatures fall most quickly, as their large surface area to volume ratio facilitates heat loss while vasoconstriction minimizes heat supply from blood flow. Under certain conditions, cold induced vasodilation (CIVD), a transient increase in blood flow, may occur, offering some protection against cold injury in the extremities.[38,39] Shivering increases in response to lowered skin temperature and increased heat loss. Shivering increases metabolic heat production through involuntary, repeated, rhythmic muscle contractions and may reach two to three times resting metabolism during sedentary exposure to cold air.[40] Although a higher rate of heat production could be obtained with exercise, shivering can be sustained longer.

Cold strain can occur if clothing has insufficient insulation or if vapor transfer is limited, resulting in wet skin or damp clothing, which increases conductive heat loss. During exercise in PPE, individuals may actually experience heat strain, but sweat accumulation in clothing may decrease insulation, thereby increasing susceptibility to hypothermia upon subsequent rest.[5] Excessive cold stress can result in a variety of cold injuries.[8] Nonfreezing cold injuries may occur if the skin stays cold and wet for extended periods of time. Freezing cold injuries (frostbite) occur when skin temperature falls below freezing. Hypothermia occurs when heat loss exceeds heat production and body core temperature falls below 35°C. U.S. Army guidance for prevention and management of cold-weather injuries is published in Technical Bulletin Medical 508, *Prevention and Management of Cold-Weather Injuries*.[8]

Laboratory Studies

The U.S. military has extensive experience evaluating PPE and has established standard test procedures to ensure quality data are obtained for assessing PPE performance with respect to thermal stress. Recently, ASTM F2668-07, "Standard Practice for Determining the Physiological Responses of the Wearer to Protective Clothing Ensembles,"[41] was written to outline procedures for evaluating the physiological strain associated with protective clothing such as firefighter, hazardous materials, or bomb suits. This standard details specific test methodology, physiological measurements, and safety limits associated with heat and cardiovascular strain that may develop with use of protective clothing during exercise, even in a temperate condition. While many of these procedures are similar to those used in military test facilities, some differences exist, as outlined in the Appendix.

Laboratory testing in environmental chambers allows control of variables to create the same conditions each day. This allows any differences observed between experimental trials to be attributed to the PPE tested, rather than being confounded by variability in test conditions. Typically, a repeated measures design is used, where the same subject performs trials with each experimental PPE and the control, in random or balanced order. This removes variability due to individual characteristics and makes differences due to the PPE easier to detect.

Use of Humans in Research

For any clothing evaluations using human test volunteers, investigators must adhere to guidelines established for research with humans, such as outlined in the Belmont Report or Declaration of Helsinki. Any evaluation that uses human volunteers must be detailed in a protocol, which undergoes both scientific and human use review by institutional review boards. The conditions of the study may be limited by scientific or ethical reasons associated with exposure of human volunteers to stressful environments.

Test Volunteers

Ideally, volunteers are representative of the population that will use the particular PPE being evaluated. Volunteers selected as test subjects should be healthy, physically fit, and medically screened (physical exam and history) to participate in the study. These requirements are to ensure they are able to complete the exercise and thermal stress required by the study. Volunteers will be excluded if they have any medical condition that indicates the conditions of the study (e.g., heat or cold exposure, exercise) would pose greater than normal risk. Volunteers may also need to meet test-specific criteria, such as limits on use of alcohol, nicotine, dietary supplements, or medications that could alter their thermoregulatory responses. Female volunteers must not be pregnant and not plan to become pregnant for the duration of the study.

Statistical determination of the number of subjects required for testing is conducted as a sample size estimation, based on the expected difference in a criterion measurement and the standard deviation in that measurement.[42] These will determine the minimum number of subjects required to test the null hypothesis that there is no difference between experimental PPE and the control (generally the currently accepted PPE). For most heat stress evaluations this is done using core temperature during exercise-heat exposure. For cold stress, skin temperature during cold exposure may be more appropriate.

Preliminary Measurements

Anthropometric data are recorded for all volunteers, including age, height, weight, body composition (typically estimated from skinfold thickness), and fitness level (based on 2-mile run time or measured during an aerobic exercise test). These data are important to characterize the population and are often used as inputs for modeling (Table I).

Heat Acclimation

Physiological responses to heat stress, including heart rate, core temperature, and sweating rate, are affected by the individual's heat acclimation (HA) status.[32] The exercise-heat stress of an experimental trial can be sufficient to begin the process of heat acclimation; therefore, trials must either be spaced far enough apart (about a week) to avoid physiological adaptations or HA is conducted before experimental trials begin to ensure those changes have already taken place. Since core temperature and heart rate are primary criteria measurements, HA is often included as part of the study to minimize variability among trials that would occur if the experimental trials were inducing physiological changes. This does not mean that the PPE can be used only in HA individuals. Exposure guidelines are developed from data obtained during the PPE evaluation but incorporate additional factors, including HA status.

Most of the physiological adaptations in heart rate, core temperature, and sweating occur by 7 days of exercise-heat exposures,[43] although fewer exposures may be required depending on the individual's initial HA status. Although some HA occurs even with passive heat exposure, more rapid changes occur when individuals exercise in the heat. Exercise for HA is typically performed continuously for 60–90 min at a moderate intensity (325–450 W),[44,45] preferably using the same mode of exercise (e.g., treadmill walking) to be used during the experimental tests. The environmental condition is chosen to provide sufficient stress to elicit adaptations in thermoregulatory response mechanisms. Hot-dry (45°C, 20% RH) conditions allow evaporation of sweat and are better tolerated by volunteers than more humid conditions and still confer adaptations that are advantageous in humid heat.[43]

Hydration should be maintained during HA sessions to promote adaptation to heat stress with minimal additional heat strain due to hypohydration.[22] This is accomplished by measuring nude body weight before and after each HA session to ensure that body weight is restored to within 1% of the baseline weight. Body weight measurements should be made at the same time of day throughout the HA process so that changes observed are more likely to reflect hydration status, rather than within-day body weight fluctuations.

Cold Acclimation

Physiological adaptations to cold stress are much smaller and occur more slowly than adaptations to heat; therefore, cold acclimation is typically not required before conducting experimental trials in the cold.[46] Furthermore, during cold stress, PPE is evaluated for its ability to limit or prevent cooling; therefore, adaptations to cold stress are unlikely to be elicited by the experimental trials themselves. Hydration status is also not critical for studies conducted in cold environments, as moderate dehydration does not significantly alter thermoregulatory responses[47] or physical performance[48,49] during cold exposure.

Familiarization

A familiarization session is conducted before beginning experimental tests to introduce volunteers to the new sensations and potential discomforts of both the test procedures and the PPE. It also affords the opportunity to fit PPE to each individual to ensure that the size is appropriate and that it is adjusted properly, particularly in combination with other equipment that may be worn during testing. To ensure insulation and heat transfer properties reflect the design of the PPE, the garment should not be so large that the material folds on itself or hangs too long, nor so short that arm and pant legs do not provide full coverage, nor so tight that underlying clothing is compressed or movement is restricted.[13] The familiarization session is also used to practice the test exercise procedures. Approximate workloads are estimated using prediction models.[50] As volunteers exercise at these levels, expired air samples are collected using open circuit spirometry, and gases are analyzed to measure how hard the person is working. Workloads can then be adjusted to achieve the desired energy expenditure.

Experimental Design

Experimental tests are conducted under the same conditions for experimental and control PPE. Tests are conducted at the same time of day, and the order of tests is balanced among volunteers. The environmental conditions, type of activity, work intensity, work/rest cycles, and exposure duration are often dictated by the intended use of the particular PPE being evaluated. For heat stress, a typical experimental test involves performing moderate intensity exercise (325–450 W) continuously for 60–90 min.[45] This design provides a long enough exercise bout to determine the rate of heat storage during steady-state work or to determine whether steady-state can be achieved in those conditions. If the intended use of the PPE indicates repeated work/rest cycles, the exposure may be changed accordingly, e.g., two 50-min exercise bouts separated by a 10-min rest period. This allows the dynamic changes that occur during rest to also be measured.

Many PPE heat exposures are short because of the stressful conditions; however, it is important to have a long enough exposure that differences among PPE can be discerned. Clothing with high insulation levels and/or low permeability may require lighter workloads and lower heat stress to ensure the ability to perform prolonged work. Such modifications of workload and environment may be made with input from biomedical modeling. Since dehydration limits exercise performance, fluid intake is recommended whenever possible (depending on the constraints of the PPE). The amount of fluid volunteers need to consume is best estimated from human simulation models that incorporate data from numerous exercise-heat exposures.[51,52]

Acceptable thermal strain levels during these controlled experiments with medical oversight may exceed those allowed under industry or military safety guidelines. Core temperature limits must be high enough to allow work in stressful conditions that is of long enough duration that differences among PPE can be observed. For most studies, volunteers are removed from the climatic chamber when their core temperature reaches 39.5°C, if they feel faint or sick, or if they no longer wish to continue. Testing should also be discontinued if there is a failure of the PPE that cannot be immediately fixed.

Environmental Conditions

Environmental conditions in the test chamber should be controlled for dry bulb temperature, dew point or wet bulb temperature, and wind speed according to the conditions required by the specific evaluation. Minimizing fluctuations in the chamber environment ensures that all PPE are evaluated under similar conditions. Wind speed must be sufficient to maintain temperature, but since increased wind can enhance evaporative cooling, it should not be too high unless a high wind speed is part of the experimental design. Black globe temperature should also be measured to determine when conditions are stable for testing, particularly when changing temperature, as chamber walls and equipment may be slower to reach ambient temperature than air. Because the goal of some evaluations is to determine how long individuals can work under a specific thermal stress while wearing a particular PPE, heat stress conditions are usually limited to no more than 49°C (120°F), 20% RH for a hot, dry environment, and 35°C (95°F), 75% RH for a hot, humid environment. For evaluations of PPE with high insulation and/or low permeability values, the hot, humid environment should be moderated (e.g., 35°C, 50% RH). This allows test volunteers to exercise for longer periods and enhances the ability to reveal differences in physiological responses between baseline and candidate PPE.

Solar radiation may be significant in desert environments or when working in an open area. Some PPE are designed to mitigate the impact of radiant heat; therefore, certain experiments may require the presence of a radiant load.[53] In this case, black globe temperature should also be measured. Most laboratory radiant sources do not provide full spectral distribution and, therefore, do not completely mimic the natural radiant environment. Any radiant source that is used for testing should be able to provide a radiant load from 500–1200 $W \cdot m^{-2}$ to simulate radiant loads from temperate through desert environments. The maximum radiant heat load of 1200 $W \cdot m^{-2}$ simulates a radiant temperature similar to working in the midday sun in the Middle East in midsummer.

Physiological Measurements

Measurements of core and skin temperatures and heart rate are important for quantifying the thermal strain of wearing a particular PPE during rest and work in thermal extremes. Metabolic rate should also be measured to quantify the work performed while wearing PPE under the conditions of the experimental trial. When exposure guidelines are developed for the PPE, work intensity and duration may be adjusted to reduce risk of heat or cold injury. Fluid intake and sweating rate data are also important for quantifying the effect of the PPE on fluid balance and evaporative cooling and can also be used later when fluid intake guidelines for that PPE are established.

An important and sensitive measurement of thermal strain is core temperature. Use of either rectal or esophageal temperature probes ensures that temperature measurements are always made at the same anatomical location without bias from external environmental conditions (such as can occur with oral or tympanic temperature measurements).[33] The esophageal probe is inserted to a depth that places it in close proximity to the left atrium; therefore, it is influenced by central blood temperature, and changes in body heat content due to exercise are reflected more rapidly in esophageal temperature than rectal temperature.[33,54] However, the esophageal probe is incompatible with respiratory masks and cannot be used during evaluation of chemical protective garments. Another disadvantage of esophageal temperature measurement is that values are impacted by swallowing (i.e., saliva or fluid). For many PPE studies, rectal probes may be more suitable, particularly when rapid changes in body temperature are not anticipated due to the study design.

A more recent method of measuring core temperature is with an ingestible telemetric core temperature pill. This technology has been demonstrated to be accurate and reliable during periods of increasing and decreasing body temperature.[54] The pill is typically given 4–8 hr before testing to ensure that it has moved from the stomach into the intestinal tract before testing begins. Since it is not in a stable position in the body, some changes in temperature may reflect location (e.g., higher when the pill is near more metabolically active tissue such as the liver) rather than actual changes in body temperature.[55] Transit time varies, which can be a problem when a series of trials are scheduled. If the volunteer excretes the pill on the morning of a scheduled trial, another pill must be given before testing begins. These pills can also be used as a rectal suppository and in this placement would be stable for the duration of the environmental exposure. Temperature pills are often preferred during field studies where volunteers need to be free to move without being encumbered by a hardwired connection to a temperature probe.

Skin temperature is measured both as an indication of thermal strain and, in combination with core temperature, to calculate mean body temperature, which is used to determine heat storage. Skin temperature at a specific site may be of interest, but typically, a mean weighted skin temperature is calculated from several sites using any one of a number of accepted weighting formulas.[56,57] During cold stress with a potential for local cold injury (typically on the face, hands, or feet), skin temperature may be measured at a larger number of sites, and mean skin temperature equations may include extremity temperatures.[57] Sensors that measure both heat flux and skin temperature are often used during cold exposure to obtain data on dry (convective and radiative) heat loss.

Thermometric determination of rate of heat storage (S, $W \cdot m^{-2}$) is calculated as mean body weight (kg) during each experimental trial $\times$ the specific heat constant ($0.965\ W \cdot h \cdot {}^{\circ}C^{-1} \cdot kg^{-1}$) / body surface area ($m^2$) $\times$ the change in mean body temperature (°C) per unit exposure time (h).[58] The weightings of skin and core in the calculation of mean body temperature may vary depending on the environment. For example, during heat stress, core temperature is weighted at 0.8–0.9 and skin at 0.2–0.1.[58,59] During cooling, the lower skin temperature may be weighted as high as 0.35.[58,60]

Heart rate reflects both increased metabolic rate due to exercise, and increased cardiac strain due to thermal stress. It is traditionally measured using bipolar electrodes, but these rarely remain in place with the high sweat rates that occur during exercise in hot environments. A more reliable method is the use of an electrode band worn around the chest with signal transmitted to a wristband receiver. Metabolic rate during exercise is measured during familiarization when determining the settings (e.g., treadmill speed and grade) required for eliciting target work rates. It is also collected at least once during a steady-state period of each experimental trial to ensure consistency among tests or to detect any differences due to variations in the tested PPE. If PPE tests require wearing gas masks, metabolic rates cannot be measured by standard indirect calorimetry during testing without modifying or interfering with the mask itself. In this case, the metabolic value collected during the familiarization phase is used as the approximate workload for all tests.

Sweating rate is important for understanding how PPE may affect hydration status. It is most often measured indirectly by correcting weight loss for liquids and solids ingested and excreted. Sweat capsules can be used but only measure a small surface area, and since sweating rate can vary over different regions of the body,[61,62] a single site does not necessarily reflect whole-body sweating rate. Sweat capsules also can be difficult to use under clothing and in humid conditions. Both nude and dressed weights are recorded before and after every environmental exposure. The difference between nude and dressed weights measured before the experimental trial indicates the weight of PPE and any additional equipment worn.

Sweat accumulation in PPE (i.e., unevaporated sweat) can be determined from the difference between pre- and post-trial clothing weight. Actual sweat loss is determined from the difference in pre- and post-trial nude weights, adjusted for food and fluid ingested and any elimination from the body. These values, corrected for respiratory water loss and CO_2-O_2 exchange,[63] are used to calculate total sweating rate, expressed per unit time and per unit surface area ($mg \cdot cm^{-2} \cdot min^{-1}$).

Evaporative cooling from the PPE can also be determined from the difference between total fluid loss and moisture retained in the garment.

Although not directly used as part of the thermal evaluation of PPE, subjective measurements are often collected to provide additional information on user acceptability that can be of use to PPE developers. At set intervals during the environmental exposure, e.g., toward the end of each rest and exercise period, subjects may be asked to rate their perception of effort,[64] thermal sensation,[65] or thermal comfort.[66] Skin moisture or wettedness increases when unevaporated sweat accumulates, and this, along with skin temperature, can impact comfort.[67,68] Additional questionnaires can be administered to collect data on garment comfort, including fit and feel (e.g., stiff, scratchy).[68]

Data recorded at least every 5 min allow trends to be observed, although less frequent time points may be used for statistical analyses. Core and skin temperature, heart rate, and sweating rate data are analyzed across time to demonstrate differences among PPE.

Field Studies

Human testing in field situations can also be performed; however, environmental conditions cannot be controlled as they are in environmental chambers. Meteorological measurements are recorded to demonstrate consistent conditions across test days, and locations of field tests are typically tested in places that have fairly consistent day-to-day weather during the time of year that testing is scheduled. If consistent environmental conditions are uncertain, one approach is to have different groups of subjects wear the different PPE configurations on the same day. This requires a larger number of subjects than the repeated measures design used in the laboratory, where each subject serves as his or her own control and variability are minimized. Furthermore, a large number of prototype garments is required to outfit independent groups.

In addition to natural variation in environmental conditions, control over volunteer activity can be difficult in a field environment. Road marching is one task that can be successfully used for PPE evaluations. If marching time is recorded over a measured distance, then metabolic rate can be estimated using prediction models,[50] and core temperature and heart rate data can be related to this metabolic rate.

Cost

Human testing includes the costs of medical evaluations for volunteers, providing staff for safety monitoring and study administration, and collecting data, including running environmental chambers and providing all test equipment. The cost of human testing increases with the complexity of experimental design, i.e., the number of PPE tested, range of environmental conditions, work/rest cycles, and number of subjects. Field studies bear the expense of transporting all the monitoring equipment and research staff to the remote site required to carry out the study. Furthermore, unlike laboratory studies conducted in environmental chambers, equipment for field studies must be able to accommodate free-ranging individuals undergoing a wide variety of tasks. This typically requires untethered monitoring equipment.

Documentation of Results

Evaluations of PPE are often required for decisions on further development, modifications, or acceptance of the garment. The primary results are provided in a brief report that documents the key findings and comparisons. For example, final core temperature or endurance time (time to reach a target core temperature), and changes in core temperature, heart rate, sweating rate, and rate of heat storage may be presented for each PPE tested in each environment. This information will indicate whether heat strain is significantly different among the tested PPE. For example, Figure 2 shows the core

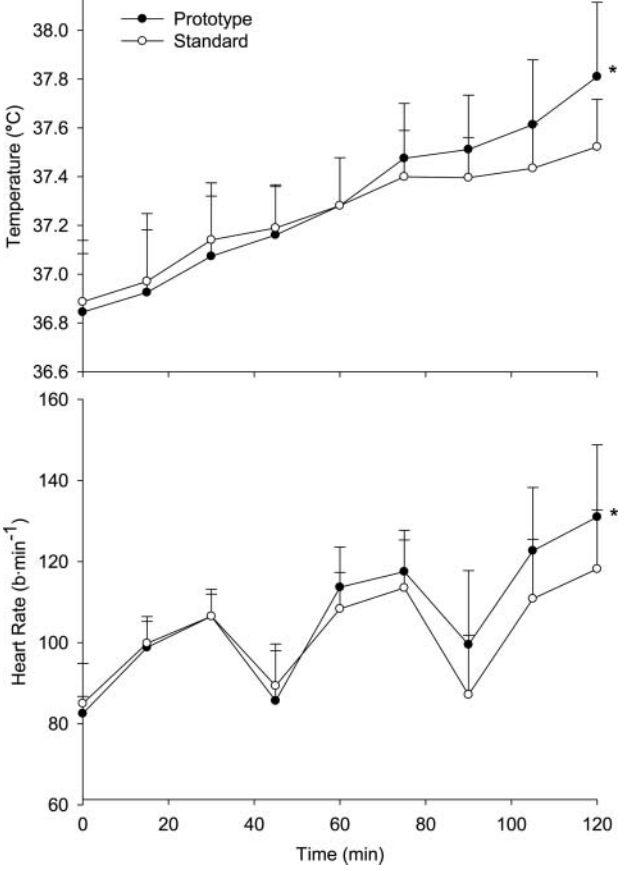

FIGURE 2. Core temperature and heart rate responses during exercise in full (with mask and in-line blower) chemical/biological protective clothing at 30°C, 30%RH, 0.9 m·s^{-1} wind. Three 30-min walks (~300 W) were separated by 15-min rest periods. The standard U.S. Air Force chemical/biological protective coverall was compared to the prototype Joint Protective Aircrew Ensemble.[12] Both core temperature and heart rate were higher when wearing the prototype ensemble, which had more chemical/biological protection, but also a lower evaporative resistance (i_m/clo). * indicates a significant ($p < 0.05$) difference between uniforms at 120 min.

temperature and heart rate responses during an evaluation where the prototype—a uniform with greater chemical and biological protection—resulted in greater thermal strain than the existing standard. In this case, the benefit of a higher level of protection must be weighed against the reduced evaporative resistance that results in higher heat strain. By comparing human physiological strain for prototype PPE and existing PPE, and using modeling to predict physiological strain under a wider range of conditions, potential hazards for thermal strain can be identified. This may result in recommendations for modification of the new PPE or imposition of limitations of thermal stress, exposure duration, work rate, work duration, or work/rest cycles.

SUMMARY

This article describes a progressive approach to the evaluation thermal stress associated with PPE, including (1) biophysical measurements of the thermal insulation and moisture permeability of the textiles using a guarded hot plate and of the PPE using thermal sweating manikins; (2) biomedical modeling to predict physiological (body temperatures, sweating rate, and heart rate) strain expected of persons wearing a particular PPE configuration under given conditions of environment (temperature, humidity, air motion, radiant lead) and metabolic rate (work, rest); and (3) testing of PPE with human test volunteers exposed to a variety of controlled (laboratory or field) environmental and metabolic stressors. These data are used to quantify how new PPE performs relative to existing standards and to guide materiel and doctrine development.

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APPENDIX

Test methods used in U.S. military laboratories differ in several ways from the recommendations of ASTM F2668-07, "Standard Practice for Determining the Physiological Responses of the Wearer to Protective Clothing Ensembles."[1] Specifically, military volunteers are not screened for participation based on height, weight, or maximal aerobic capacity. Active duty military personnel who are fit for duty and pass a medical evaluation specific to the stresses of the study are considered for participation. It is desirable to include females

if the PPE would be used by them. Although there is an upward shift in the thermoregulatory set point in the luteal phase of the menstrual cycle,[2] by looking at changes in thermoregulatory responses rather than absolute temperatures, differences observed between the prototype PPE and control are generally larger than differences in thermoregulatory responses due to cycle phase. Restrictions on exercise are not as broad as in ASTM F2668-07. Military personnel are only restricted from vigorous exercise 12 hr before testing, which ensures that they are rested for testing the next day without limiting their participation in military duties. Skin temperature sites may vary based on the particular uniform tested. For safety limits, a higher core temperature of 39.5°C is used rather than the conservative limit of 38.5°C of ASTM F2668-07. This allows volunteers to complete longer exercise-heat exposures to more clearly demonstrate differences among PPE without increasing risk of heat illness, since controlled laboratory conditions allow rapid cooling if a volunteer reaches a core temperature limit and is removed from the chamber to a cooler environment. Test duration may exceed 2 hr, depending on the mission requirements associated with the specific PPE being tested. Finally, the suggestion that 1–1.5 L water be ingested 1–2 hr before testing is excessive and would likely require urination during the test, which would compromise data collection.

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